Searching for new physics with future CMB experiments

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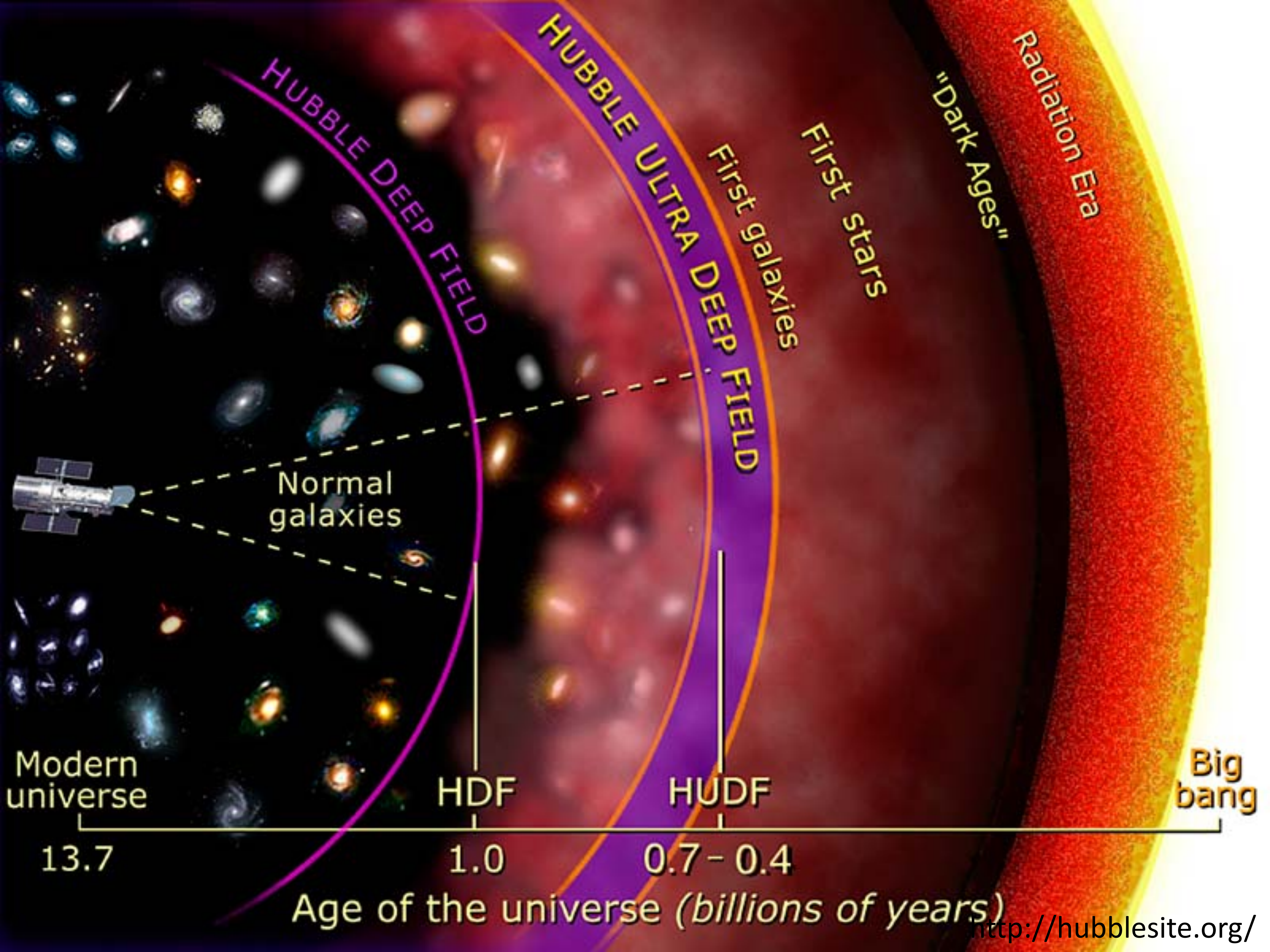
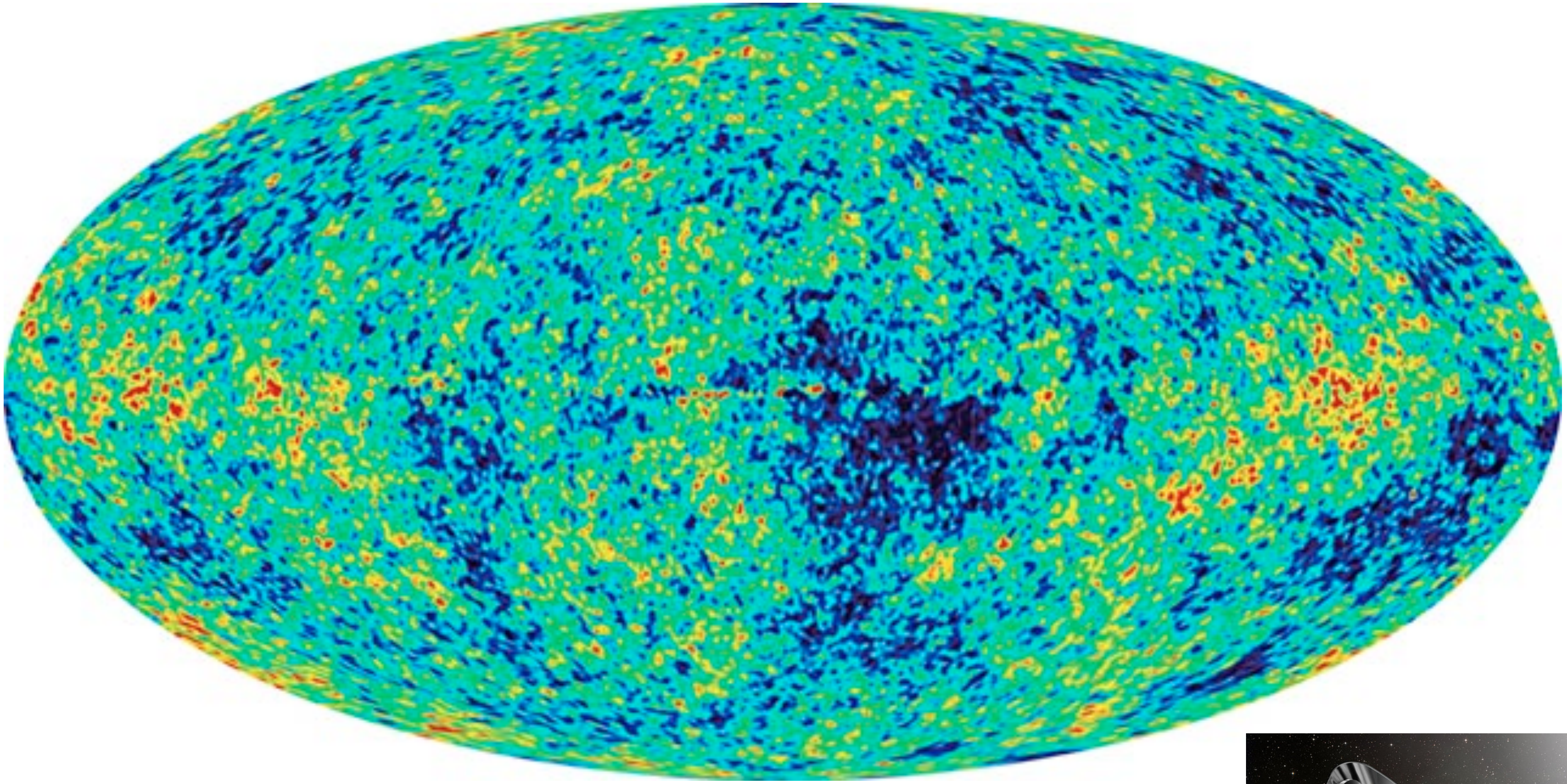
SFU

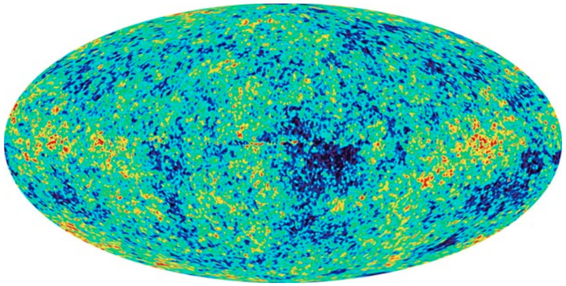


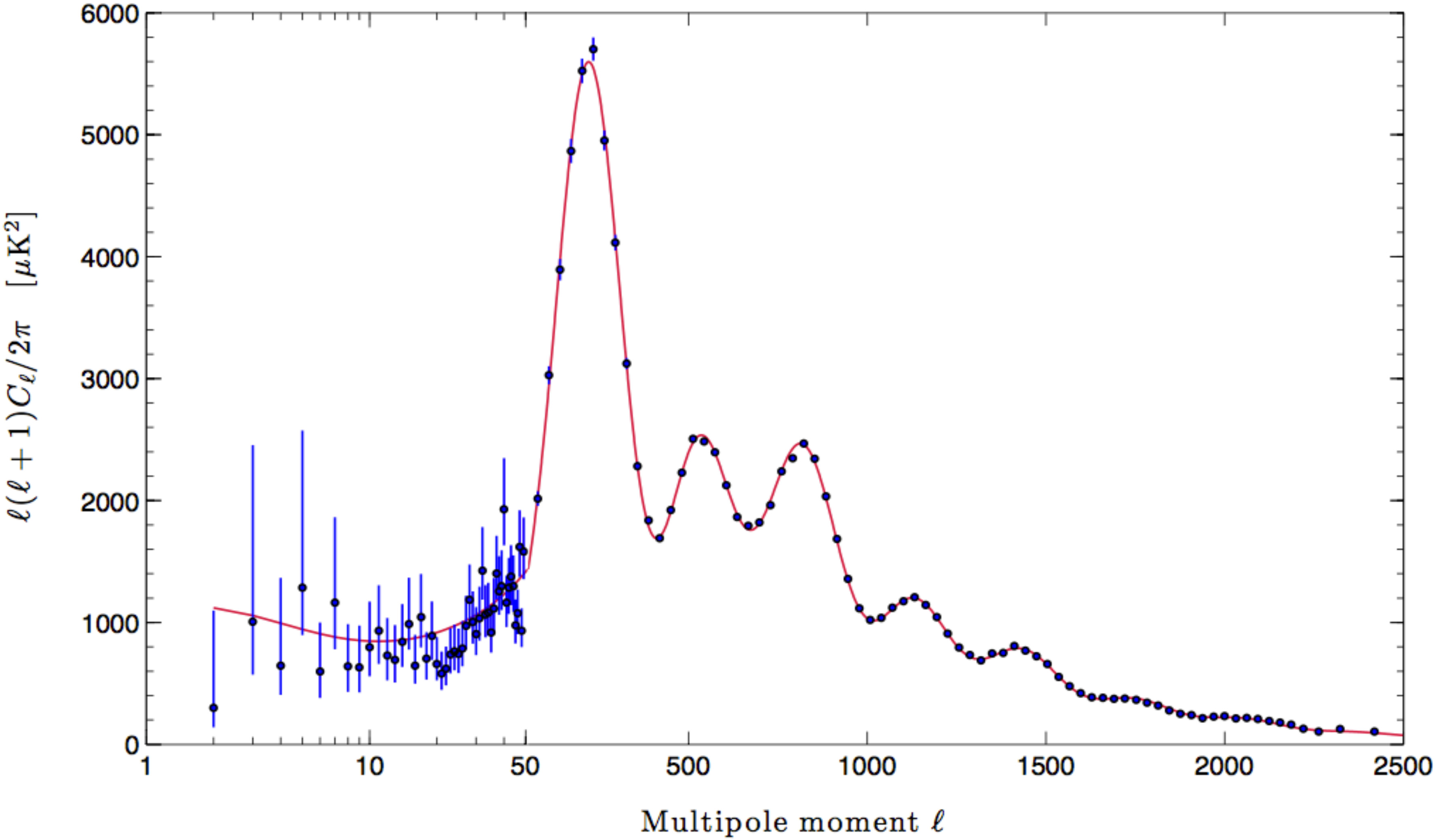
http://hubblesite.org/

Universe @ 400,000 years of age



The CMB temperature anisotropy spectrum





Facts from CMB	**Prediction of simplest models of inflation**
Almost isotropic	Homogeneity
Practically flat	Flatness
Small Gaussian fluctuations	Small Gaussian fluctuations
Adiabatic initial conditions	Adiabatic initial conditions
Almost scale-invariant spectrum	Almost scale-invariant spectrum
A bound on the gravitation wave background ($r < 0.1$)	Gravitational wave background (but does not predict the amplitude)

Status of Inflation

Accepted as a working paradigm

Quantum uncertainty as the origin of fluctuations is a beautiful idea

Open questions:

- ○ when did it happen?
- ○ what was before inflation?
- ○ what are the conditions for inflation to start?
- ○ what is the “inflaton”?
- ○ is it related to known particle physics?

Remaining prediction, AKA “the smoking gun”:

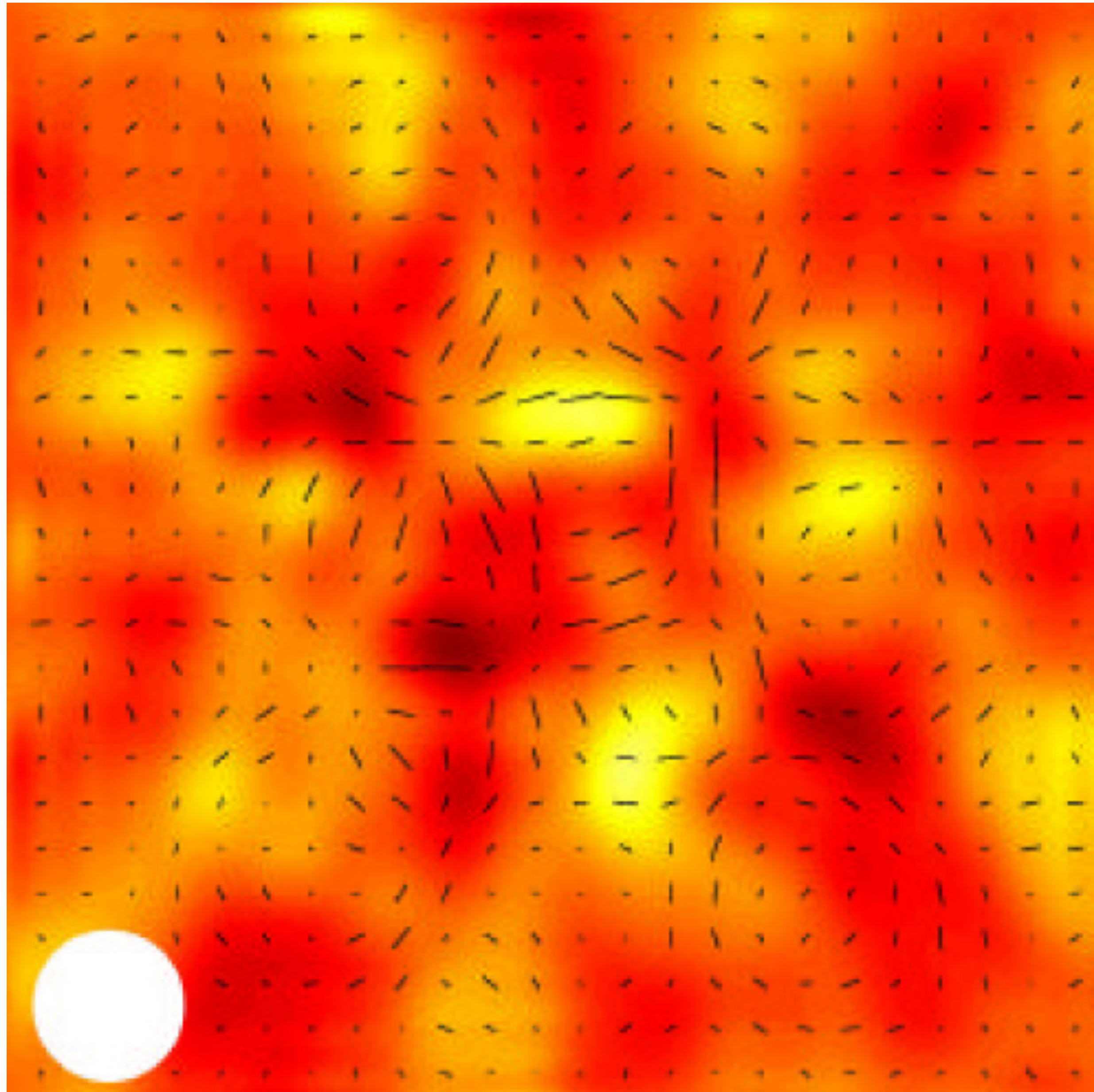
a background of gravity waves

CMB Polarization

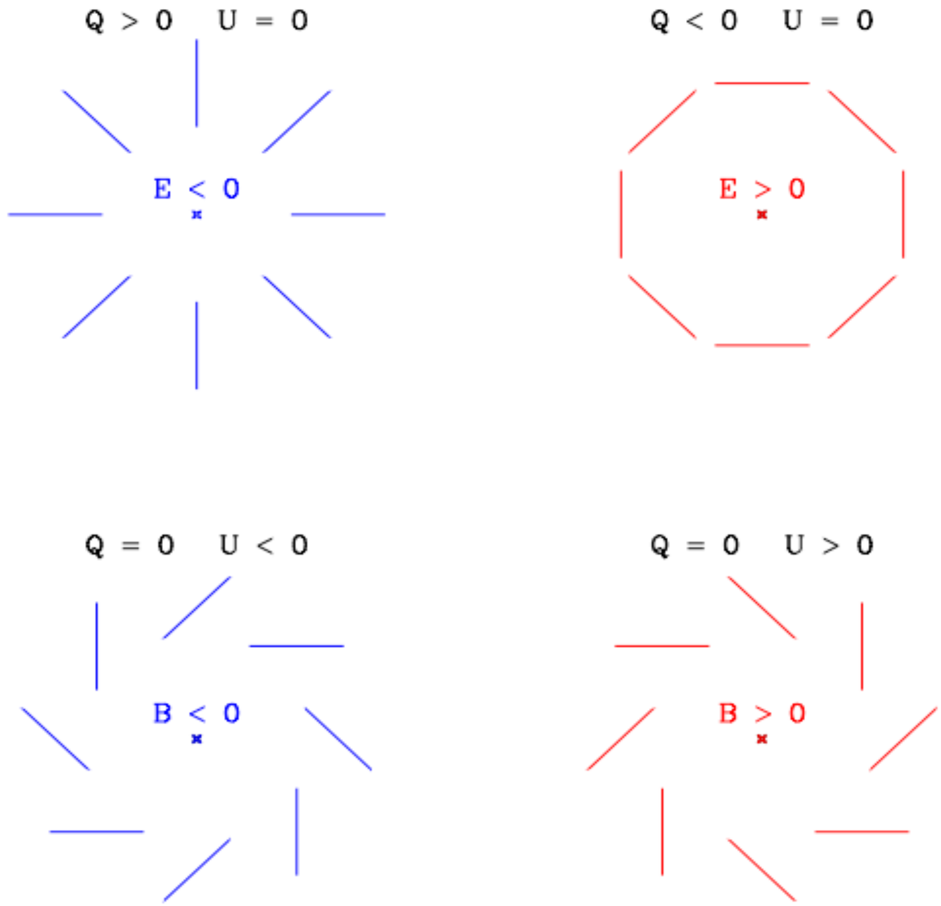
DASI
2002

$$P = \sqrt{Q^2 + U^2}$$

$$\alpha = \frac{1}{2}\arctan(U/Q)$$

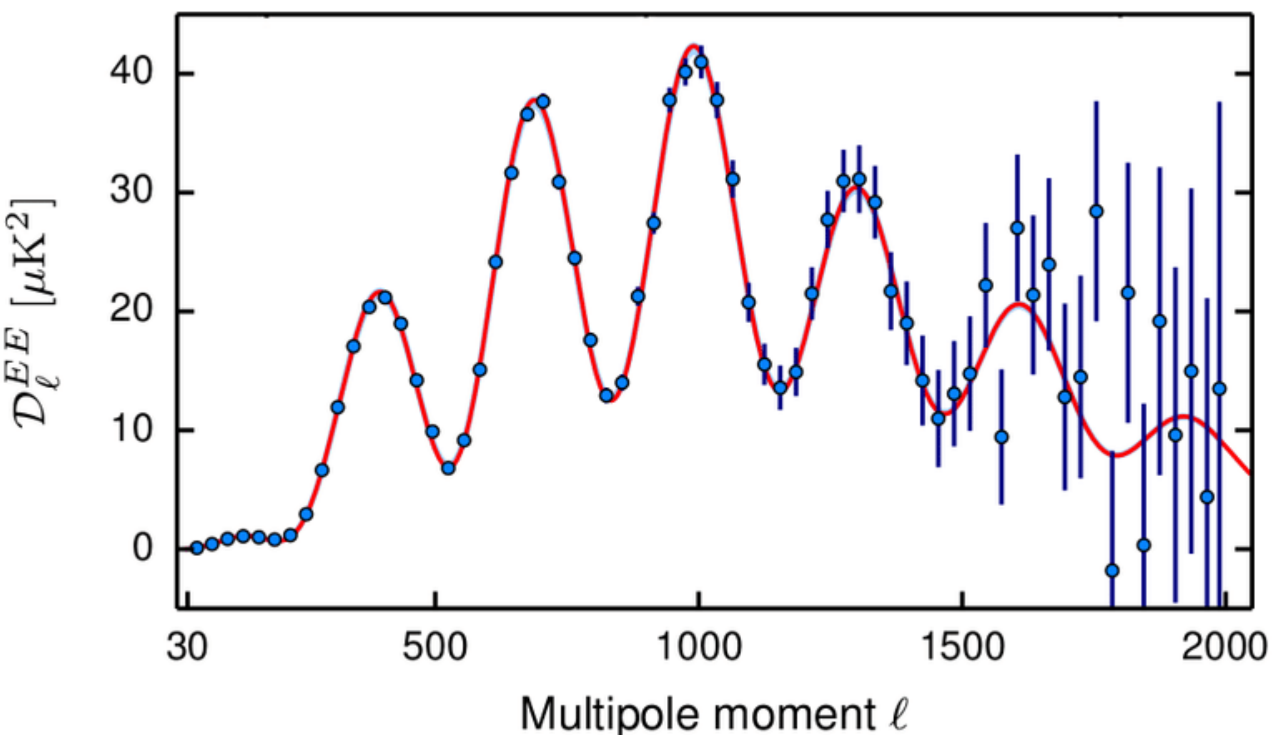


E (parity-even) and B (parity-odd) modes

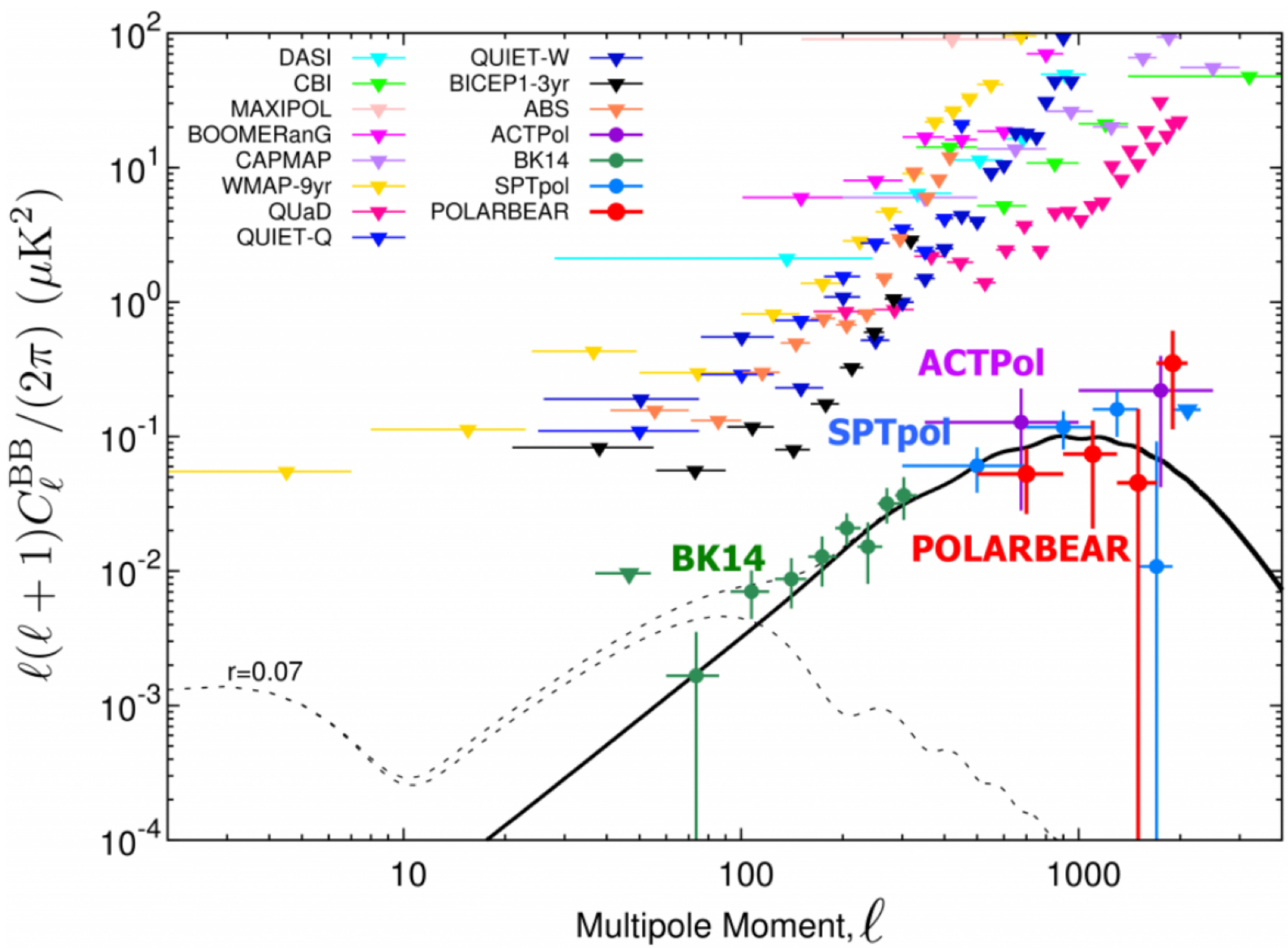


from M. Zaldarriaga, astro-ph/0305272

The "E-mode" polarization spectrum



The "B-mode" polarization spectrum

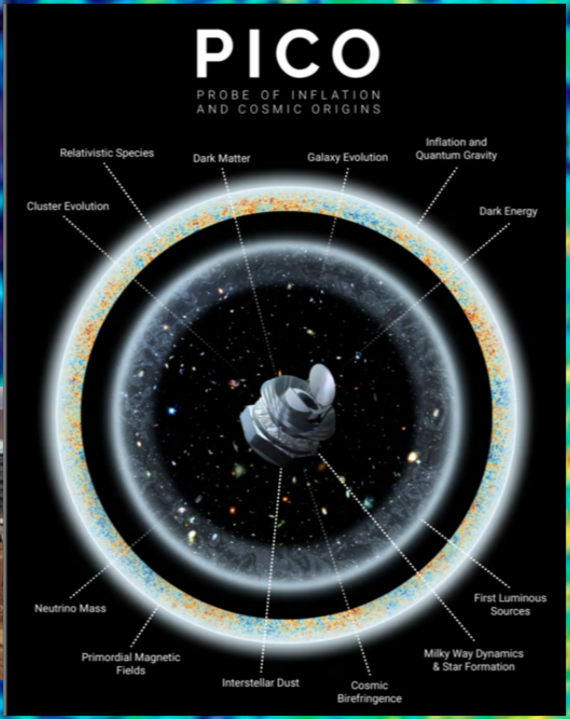



BICEP/Keck


SPT

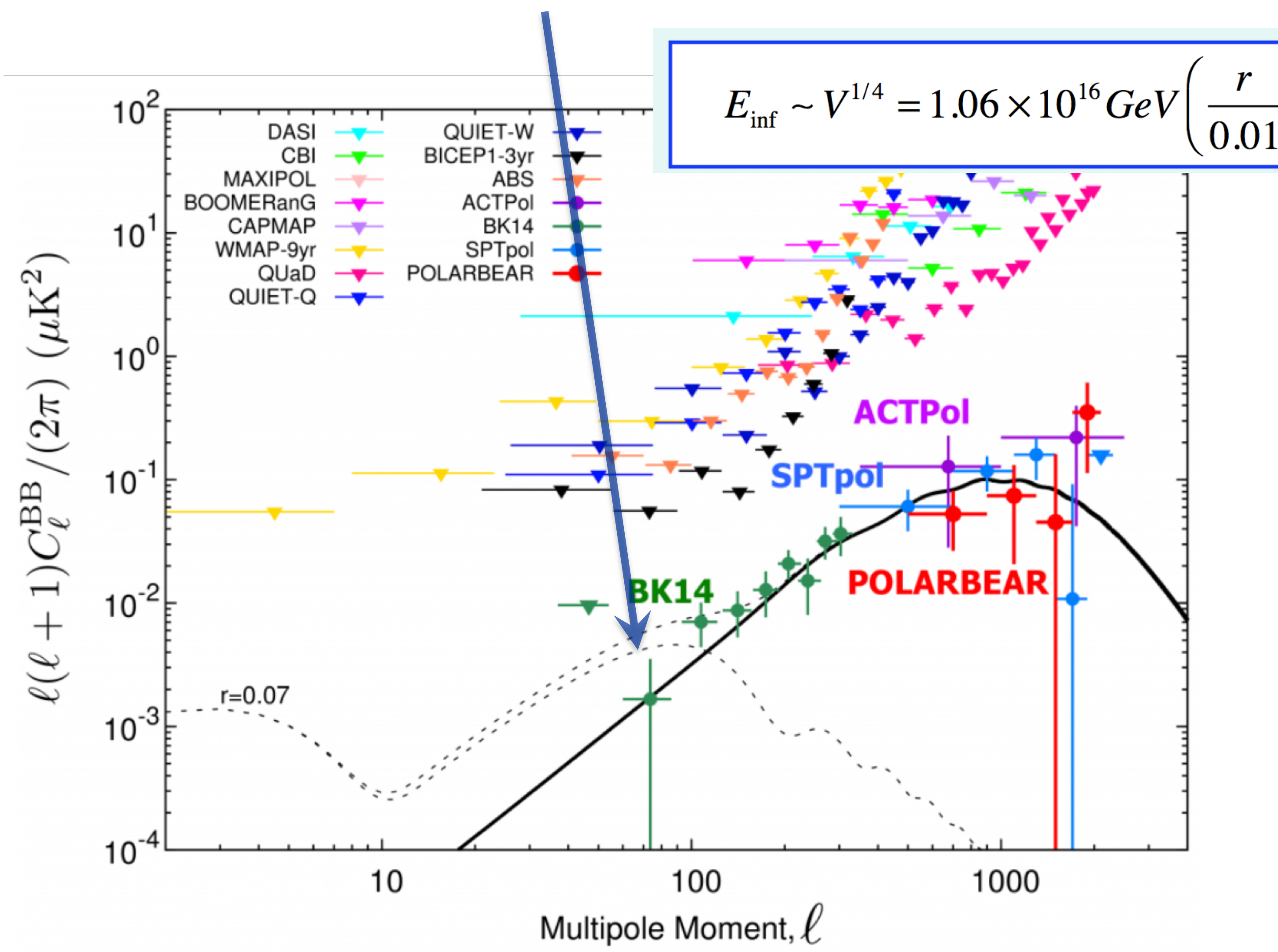

Simons Observatory
SIMONS OBSERVATORY


CMB-S4
Next Generation CMB Experiment


PICO
PROBE OF INFLATION AND COSMIC ORIGINS
Relativistic Species
Dark Matter
Galaxy Evolution
Inflation and Quantum Gravity
Cluster Evolution
Dark Energy
Neutrino Mass
First Luminous Sources
Primordial Magnetic Fields
Interstellar Dust
Cosmic Birefringence
Milky Way Dynamics & Star Formation

The "smoking gun" of inflation

$$E_{\inf} \sim V^{1/4} = 1.06 \times 10^{16} GeV \left(\frac{r}{0.01}\right)^{1/4}$$



A positive outlook

Whether or not we detect the "smoking gun" of inflation, we have entered the era of precision B-mode science

Other fundamental physics can be studied with B-mode polarization:

- light relics, neutrinos
- primordial magnetic fields
- phase transitions, cosmic defects
- birefringence, pseudoscalars
- dark energy, modified gravity
- …

Even relatively mediocre B-mode data provide useful information

Cosmic Magnetic Fields

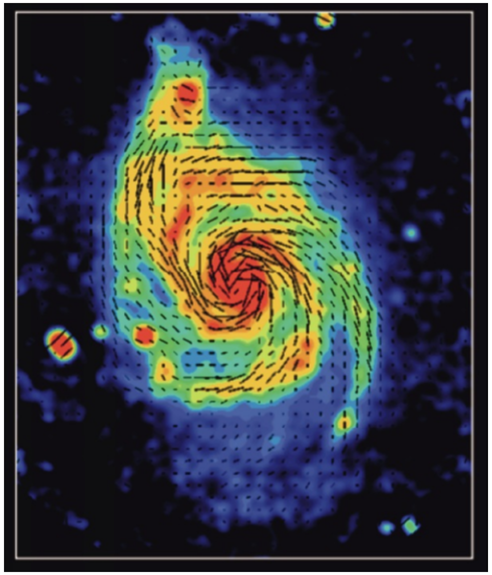


Image courtesy of NRAO/AUI

- Origin of 1-10 μG fields in galaxies and clusters
  - purely astrophysical? (dynamo, SN, …)
  - purely primordial? (need nG coherent on 1 Mpc)
  - some combination of the two?
- Evidence of magnetic fields in voids?
  - missing GeV γ-ray halos around TeV blazars
- Generated in the early universe – not "if", but "how much"
  - phase transitions
  - inflationary mechanisms
  - a window into the early universe
- A distinct signature in CMB could prove their primordial origin
  - Current upper bounds from CMB are at 1 nG level
  - PICO, CMB-S4 can go below 0.1 nG and rule out the purely primordial origin of galactic fields

Magnetic field effects on CMB

- Gravitational

$$T^0_0 \propto -B^2$$
$$T^i_j \propto B^2\delta^i_j - 2B^iB_j$$

scalar (curvature), vector (vorticity), tensor (gravitational waves) metric perturbations

- Electromagnetic

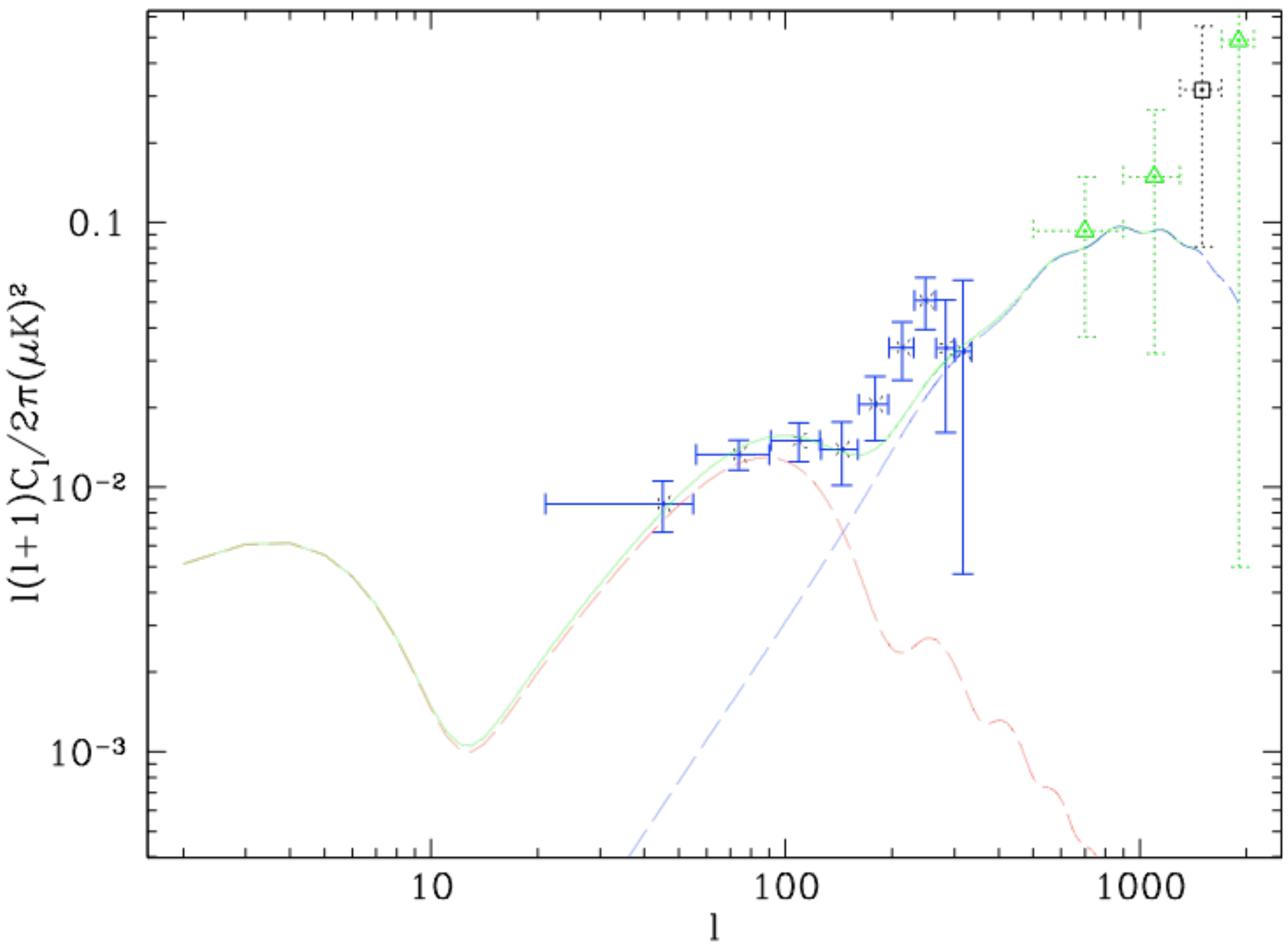
Lorentz force causes vorticity in plasma

Magnetic energy dissipates, dumps energy into the plasma

- spectral distortions
- modified ionization history

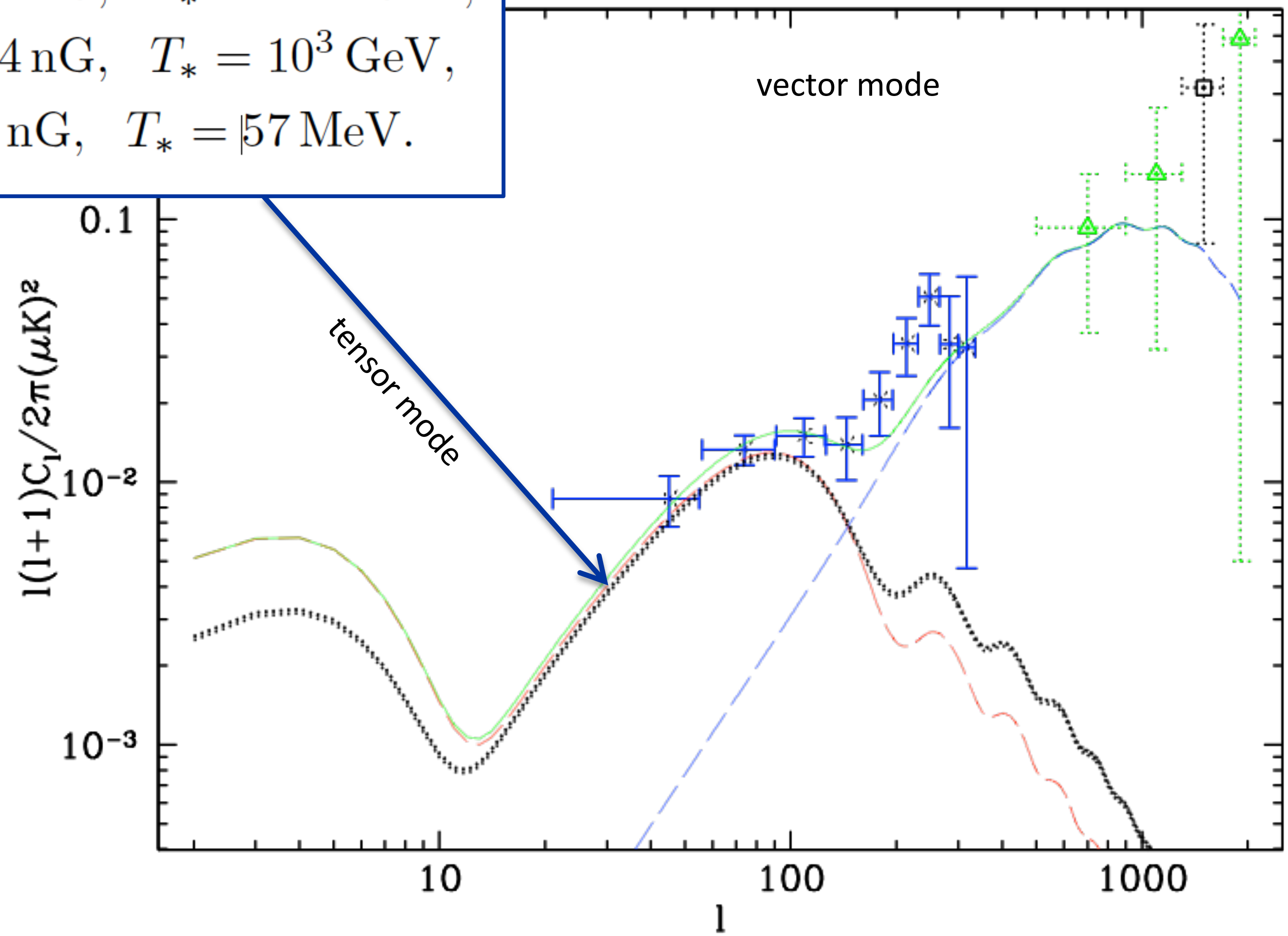
→ Faraday Rotation

Magnetic field contributions to the B-mode spectrum



Magnetic field contributions to the B-mode spectrum

$$B_1 = 1.83\,\mathrm{nG}, \quad T_* = 10^{14}\,\mathrm{GeV},$$
$$B_1 = 3.04\,\mathrm{nG}, \quad T_* = 10^{3}\,\mathrm{GeV},$$
$$B_1 = 5.5\,\mathrm{nG}, \quad T_* = 57\,\mathrm{MeV}.$$



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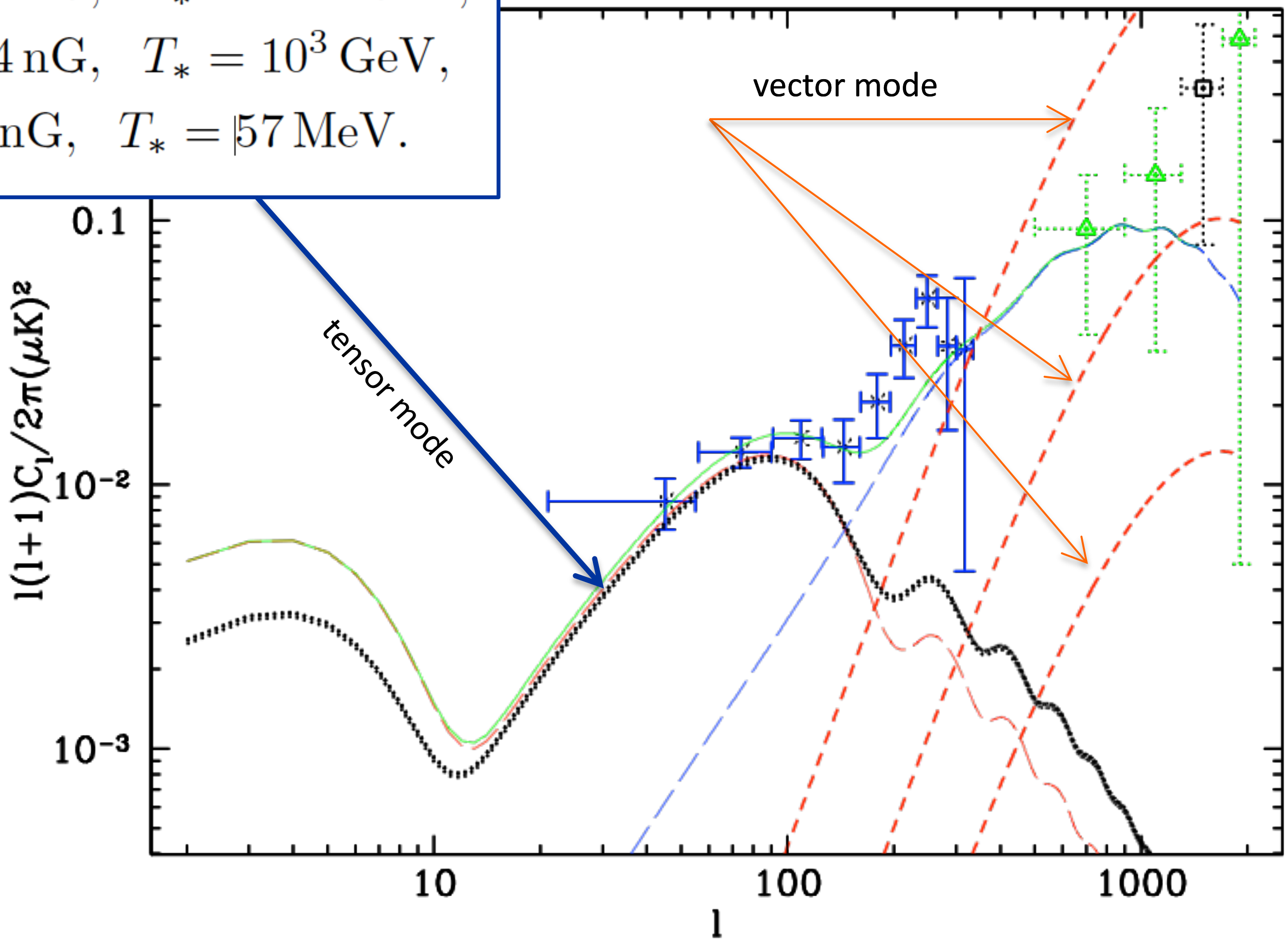

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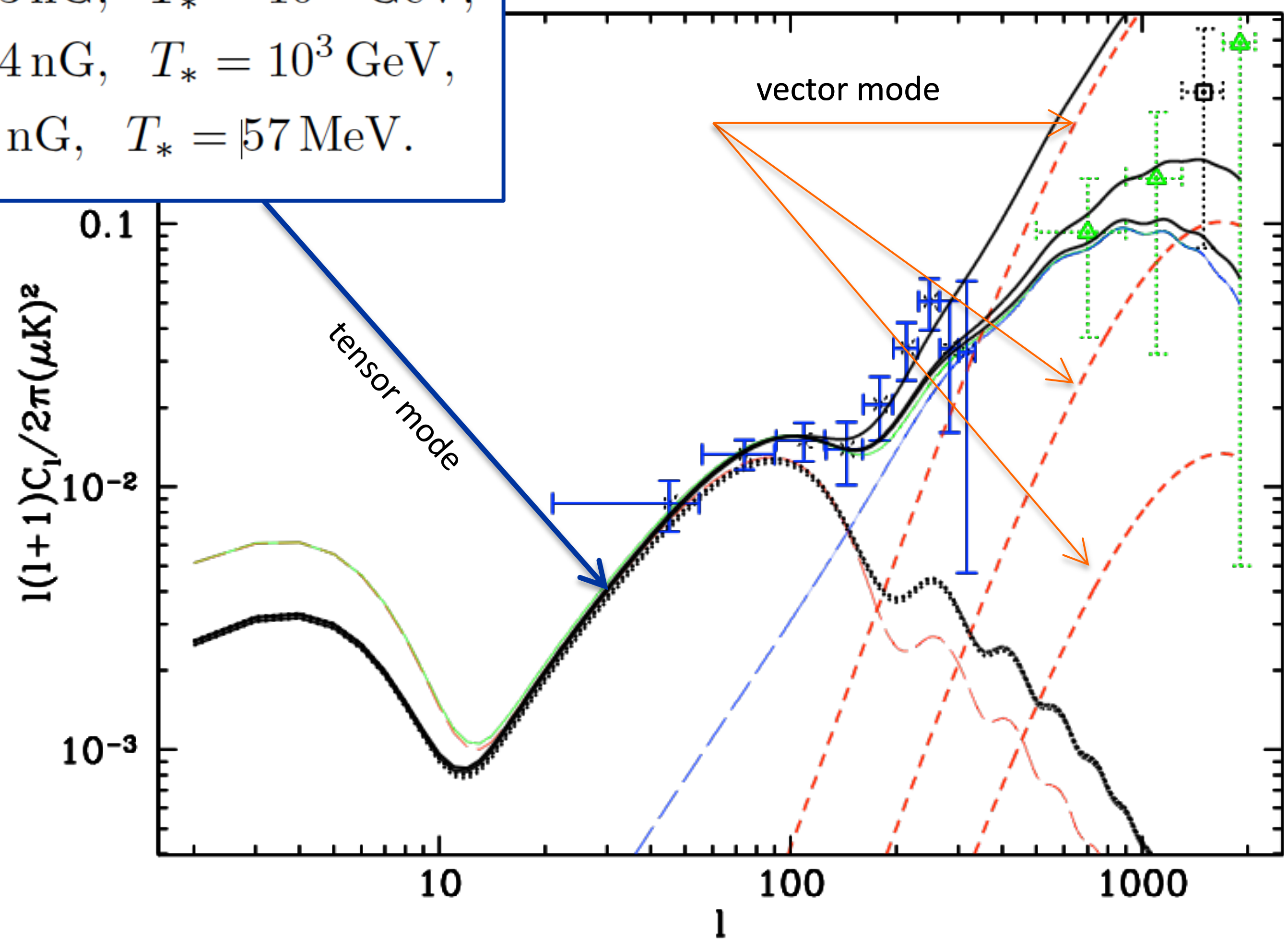
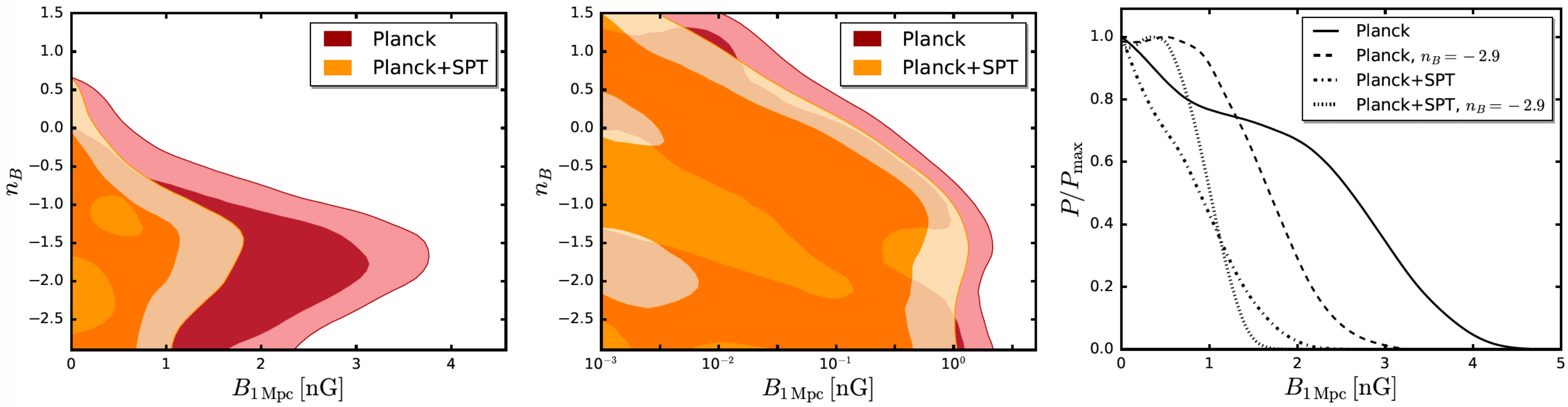


Bounds from Planck combined with SPT B-modes



- B_{1Mpc}< 1.2 nG at 95% CL for a nearly scale-invariant PMF
- Adding SPT BB reduces the Planck bound on B_{1Mpc} by a factor of 2

A. Zucca, Y. Li, LP, 1611.00757, LP & A. Zucca, 1801.08936

Crossing the nano-Gauss barrier

- Magnetic stress-energy is quadratic in B

$$
\begin{aligned}
T^0_0 &\propto -B^2 \\
T^i_j &\propto B^2\delta^i_j - 2B^iB_j
\end{aligned}
$$

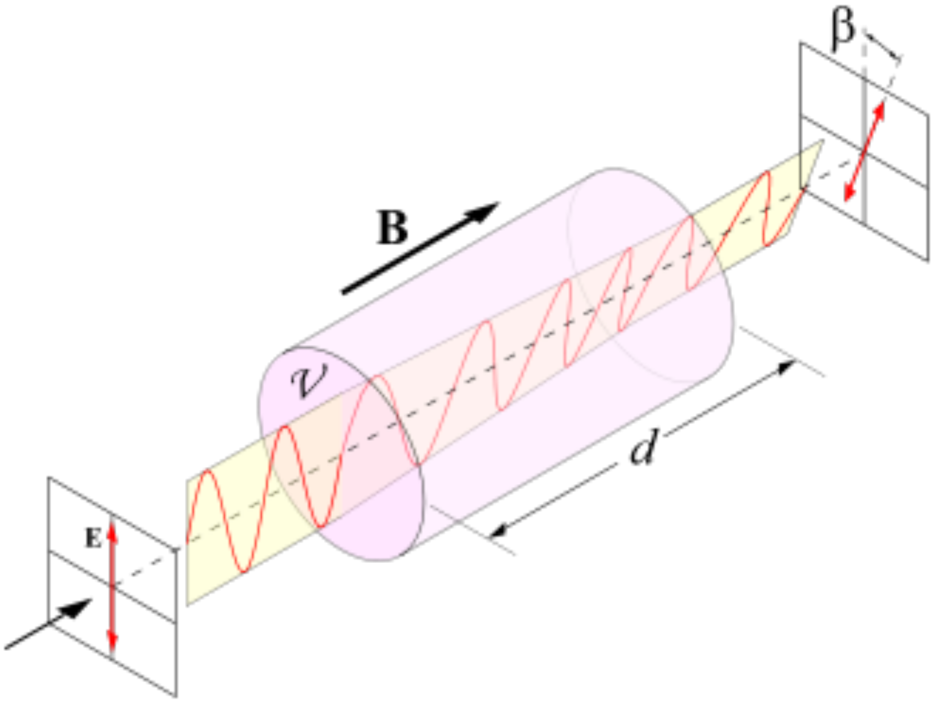
- Thus, CMB spectra are quartic in B, i.e. $C_L \sim B^4$

- Bounds based on CMB spectra will always remain at O(nG)*

*Potentially very strong bounds from modified recombination history
Jedamzik and Abel (2011, 2013), Jedamzik and Saveliev, 1804.06115

Faraday Rotation is linear in B

Faraday Rotation



- For CMB: $\alpha(\hat{\mathbf{n}}) = \frac{3c^2\nu_0^{-2}}{16\pi^2 e}\int \dot{\tau}\;\mathbf{B}\cdot d\mathbf{l} = c^2\nu_0^{-2}\;\mathrm{RM}(\hat{\mathbf{n}})$

- Most of the rotation occurs at last scattering (if there is a PMF) and inside our galaxy

Faraday Rotation converts E-modes into B-modes

$$B_{lm} = 2 \sum_{LM} \sum_{l'm'} \alpha_{LM} E_{l'm'} \xi^{LM}_{lml'm'} H^{L}_{ll'}$$

One can reconstruct the rotation angle from mode-coupling EB correlations
(Kamionkowski, 2009; Glusevic, Kamionkowski, Cooray, 2009)

$$\hat{D}^{LM,\mathrm{map}}_{ll'} = \frac{4\pi}{(2l+1)(2l'+1)} \sum_{mm'} B^{\mathrm{map}}_{lm} E^{\mathrm{map}*}_{l'm'} \xi^{LM}_{lml'm'}$$

$$[\hat{\alpha}_{LM}]_{ll'} = \frac{\hat{D}^{LM,\mathrm{map}}_{ll'}}{2 C^{EE}_{l} H^{L}_{ll'}}$$

Generalized to a multiple channel Rotation Measure (RM) estimator in LP, 1311.2926

Faraday Rotation converts E-modes into B-modes

$$B_{lm} = 2 \sum \sum \alpha_{LM} E_{l'm'} \xi^{LM}_{lml'm'} H^{L}_{ll'}$$

Reconstr … rrelations

(Kamionkov

$\hat{D}$ … $^{LM}_{ml'm'}$

Generali … estimator

in Pogosi

B = alpha* E

therefore

<EB> = alpha <EE>

then we can find alpha from

alpha = <EB> / <EE>

if <EE> is known

Forecasted 1σ bounds on a primordial magnetic field

	Planck +SPT	PB	Simons Obs	CMB-S4	PICO
Bound from BB, TT, EE, TE	1 nG	2.5 nG	1.0 nG	0.55 nG	0.5 nG
Bound from FR	n/a	50 nG	0.7 nG	0.16 nG	0.08 nG

PICO, CMB-S4 will probe ~0.1 nG and can rule out a purely primordial origin of galactic fields

LP, M. Shimon, M. Mewes, B. Keating, 1904.07855, PRD

Light pseudoscalar fields

- The QCD Axion – the Goldstone boson of an additional broken U(1) symmetry suggested as a solution of the Strong CP Problem

  (Peccei and Quinn, Phys Rev Lett, 1977)

- Axions are a leading candidate for Dark Matter

  (for a recent review see D. March, arXiv:1510.07633)

- String Theory predicts existence of many axion-like fields

  ("String Axiverse", Arvanitaki et al, arXiv:0905.4720)

- A light pseudo-Goldstone boson is a natural candidate for quintessence

  (S. Carroll, Phys Rev Lett, 1998)

Axion-like (nearly) massless pseudoscalar

$$\mathcal{L}_{int} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{a}{2f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Right- and left-handed polarization states propagate at different velocities causing the rotation of the polarization plane:

$$\ddot{A}_\pm(k,\tau) + \left[k^2 \pm \frac{2k}{f_a}(\dot{a} + \hat{n}\cdot\vec{\nabla}a)\right] A_\pm(k,\tau) = 0$$

$$A_\pm = A_x \pm i A_y$$

Uniform rotation angle

$$\alpha = f_a^{-1} \int_{\tau_{\rm dec}}^{\rm today} d\tau \dot{a} = f_a^{-1} \Delta a$$

- Can happen if the U(1) symmetry was broken before the end of Inflation: $f_a > H_{\rm I}$

- Requires a non-zero axion mass

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} \partial_\mu a \partial^\mu a + \frac{a}{2 f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} \quad - \frac{1}{2} m_a^2 a^2$$

$$10^{-33} eV \sim H_0 < m_a < H_{\rm dec} \sim 10^{-28} eV$$

- If detected, implies a global violation of parity
  - parity-odd EB and TB correlations (C_L^{EB} and C_L^{TB})

S. Carroll, astro-ph/9806099, PRL

Stochastic anisotropic rotation

- the axion mass must be a smaller than the decoupling scale

$$m_a < H_{\rm dec} \sim 10^{-28} eV$$

- If the symmetry is broken after inflation, $f_a < H_{\rm I}$
  - Global strings
  - Rotation spectrum peaked on very small scales
- If the symmetry is broken before inflation, $f_a > H_{\rm I}$
  - A scale-invariant rotation angle spectrum

(Pospelov, Ritz, Skordis, PRL, 0808.0673)

$$A_\alpha \equiv \frac{L(L+1)C_L^\alpha}{2\pi} = \left(\frac{H_{\rm I}}{2\pi f_a}\right)^2$$

Present vs future

- Current bounds (Planck, SPT, BICEP2/Keck)

  - Uniform rotation angle, $\boldsymbol{\alpha} = \Delta a/f_a < 30$ arcmin
  - Stochastic rotation generated during inflation:

$$A_\alpha < 0.11 \text{ deg}^2, \;\; f_a > 5 \cdot 10^{15} \text{ GeV} \frac{H_\mathrm{I}}{10^{14} GeV}$$

- Future bounds (CMB-S4, PICO)

  - Uniform rotation angle, $\boldsymbol{\alpha} = \Delta a/f_a < 0.06$ arcmin
  - Stochastic rotation generated during inflation:

$$A_\alpha < 0.00005 \text{ deg}^2, \; f_a > 4 \cdot 10^{17} \text{ GeV} \frac{H_\mathrm{I}}{10^{14} GeV}$$

  - Non-trivial bounds on String Theory axions and inflation

LP, M. Shimon, M. Mewes, B. Keating, 1904.07855

Summary

The main motivation for studying the CMB B-modes is to detect the inflationary gravitational waves

We can only hope that they will in the detectable range

B-modes also probe primordial magnetic fields, axion-like fields and other interesting physics

Next generation CMB experiments, like PICO and CMB-S4, will probe Faraday Rotation and constrain PMF at 0.1 nG level

They will significantly tighten the lower bound on the energy scale of the spontaneous symmetry breaking in axion models

We have entered the era of precision B-mode science - a new frontier for testing fundamental physics with cosmology